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Article title

Full Life Cycle Assessment of Two Surge Wave Energy Converters

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Abstract

Wave energy has the potential to play an important role in the UK's electricity mix in the coming years and it is important to understand the interactions of wave energy converters (WECs) with the environment before considering them viable alternatives for other technologies. The aim of this study was to identify the environmental impacts of the deployment of the Oyster WEC to the EMEC test site at Orkney, UK over its lifetime across three general categories: resource use, human health and ecological consequences. A full life cycle assessment (LCA) was performed on two different models of the Oyster WEC: Oyster 1 and Oyster 800. It was found that the latter is a fitting upgrade for its predecessor as it has lower environmental impacts in all categories; however, the high infrastructural needs of the Oyster technology makes its environmental performance worse than most other wave energy converters. Key sustainability indicators for energy converters include carbon footprint and energy payback period, and these were found to be 79 and 57 gCO_2 eq/kWh and 45 and 42 months for the Oyster 1 and Oyster 800 respectively. Although these are significantly higher than most estimates for other types of renewable energy converter, the carbon impacts are still significantly lower than for conventional fossil-fuelled power generation.

Keywords

renewable energy, wave energy, energy converter, life cycle assessment (LCA)

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Introduction

Wave energy is a promising renewable energy source, with some studies suggesting that the UK could achieve 27 GW from wave and tidal resources by 2050, if the development rate of the sector is expanded through the 2020s [1]. While there is great potential, the development rate has been poor so far due to the electricity grid infrastructure limitations and harshness of the marine environment in resource-rich areas, and the weak strategy of the government and industry in supporting wave energy innovation [2, 3]. Furthermore, the cost of wave energy remains high as it is still at an early development stage when compared to established renewable energy systems with high production capacities (e.g. wind power) [3]. The UK installed capacity of shoreline wave and tidal generation was only 20.4 MW by late 2018 [4]. Policy choices that led to premature commercialisation have, in turn, led to the liquidation of important players such as Pelamis in 2014, and Aquamarine Power (the developer of the Oyster technology) in 2015, among 12 others [2]. The cost of researching and developing new marine energy technologies remains high, and securing the necessary investment required for the deployment of commercial devices is challenging. A comprehensive understanding of the environmental impacts and benefits of existing wave energy conversion technologies can provide evidence to justify greater policy support and investment in this sector.

It is necessary for renewable power generation technologies to be assessed carefully to understand their interaction with the environment, human health and resources in order to achieve a sustainable future. Life cycle assessment (LCA) is a methodology that can be used to fulfil that necessity; LCA categorises the environmental impacts of each step in a product's life cycle. These can be considered by phase or as a whole from "cradle-to-grave", containing stages such as raw material extraction, manufacturing, transport and recycling [5]. LCA is being used in many different fields to assess environmental impacts in response to the threat of climate change and increasing energy demand [6].

A small number of LCAs of wave energy converters (WECs) have been published, with 5 identified by the authors to date. Two of these are limited in considering only embodied energy and CO_2 emissions; including studies on the Oyster 1 [7] and Pelamis [8]. Only three studies offer full LCAs of WECs; a comprehensive analysis of generic WEC concepts in the European Commission's Joint Research Centre's (JRC) ocean energy database [9], an analysis of the Wave Dragon [10], and an extended analysis of the Pelamis [11].

The aim of this study is to carry out a detailed full LCA of two versions of Oyster wave energy converter, expanding on the earlier carbon and energy audit of the Oyster 1 by Walker and Howell [7]. In addition to examining any changes in impact due to the evolution of the design from the Oyster 1 to the Oyster 800, this study also considers a broader range of environmental impact categories (e.g. acidification and eutrophication of marine environments), to identify whether the focus on carbon and energy has overlooked any key impacts, or the life cycle stages that significantly contribute to them. While some additional data on the structure of Oyster 1 and 800 were sourced from environmental and decommissioning documents [12, 13], assumptions were also required to completely model the WECs where data was not available. As in Walker and Howell [7], the prototype devices were analysed for one case study location only - the European Marine Energy Centre (EMEC) test site at Stromness, UK.

Environmental Impacts of Wave Energy

The design of wave energy converters varies widely but can be broadly categorised into attenuators, point absorbers, oscillating wave surge systems, pressure differential systems, rotating mass systems, oscillating water columns and overtopping devices [9]. As mentioned previously, only five existing published studies of the environmental impacts of WECs have been identified. One of these is a comprehensive LCA of a number of different concepts in the EC JRC ocean energy database [9], so considers the environmental impacts of all of the different types of WEC listed. The remaining three studies, however, consider three very different technologies. The only common impacts considered in these analyses were energy and carbon intensities, which were found to vary widely, and are summarised in Table 1. Of these three types of device, the Wave Dragon bears the least resemblance to the Oyster, as it is predominantly concrete, while the Oyster and Pelamis are mostly constructed of steel, with hydraulic power take-off systems.

Device	Type	Energy Intensity (kJ/kWh)	Carbon Intensity (g CO2 eq/kWh)
Oyster 1 [7]	Oscillating wave surge	236	25
Oscillating wave surge [9]	Oscillating wave surge		64
Pelamis [8]	Attenuator	293	23

Pelamis [11]	Attenuator	493	35
Attenuator [9]	Attenuator		44
Wave Dragon [10]	Overtopping	174	13

Table 1 - Summary of impacts from existing studies of WECs

With regards to other environmental impacts, the greatest impacts for the Wave Dragon were found to be global warming, human toxicity soil and bulk waste [10] and for the Pelamis they were aquatic eutrophication (P), human toxicity (soil and water), bulk and radioactive waste [11].

All studies found that the greatest environmental impacts arose during the material extraction and manufacturing stages of the device life cycle; in other words the extraction and processing of raw materials used in the wave energy converters, along with the manufacture of the converters themselves, contributed the most to their whole life cycle impacts. This is in line with numerous studies for wind power generation [14-17], but in contrast to conventional fossil fuelled power stations where the greatest environmental impacts generally arise during operation, due to the combustion of the fuel itself [18, 19].

Method

The Oyster WEC

The Oyster device was designed by Aquamarine Power Ltd, and is an oscillating flap-type surge wave energy converter that is fixed to the seabed near to shore (Figure 1) [20-22]. As a wave front passes the motion of the flap is resisted by hydraulic rams, which pump fluid through a network of pipes to shore. The conversion of wave energy to electricity takes place on shore by means of a Pelton turbine. The first-generation device, the Oyster 1, was rated at 315 kW, while the second-generation Oyster 800 (also known as Oyster 2) is rated at 800 kW (Figure 2) [12].

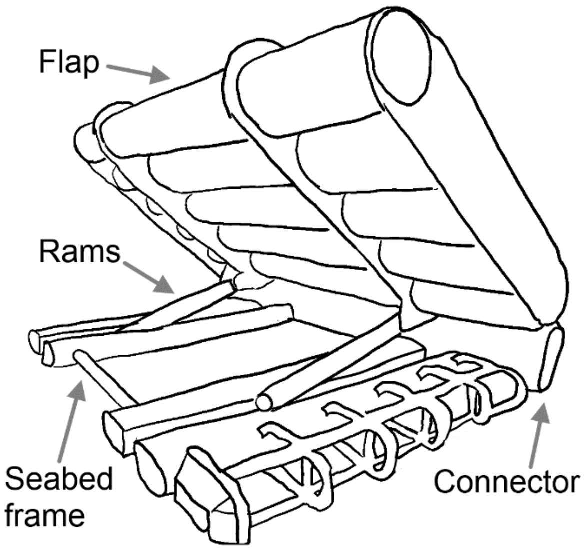

Figure 1 - Oyster 1 (after images from [23])

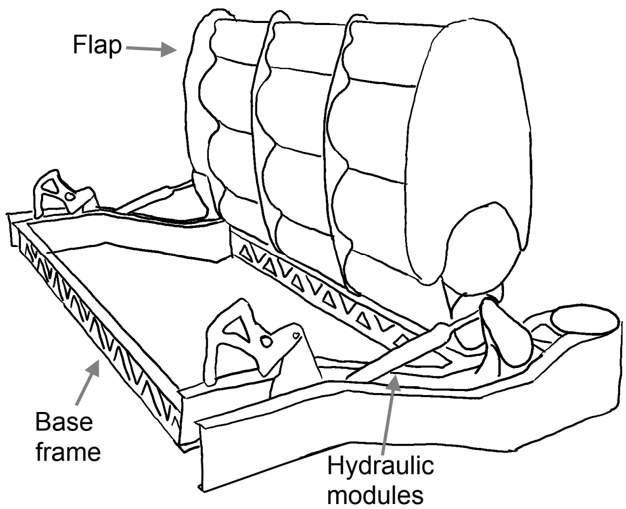

Figure 2 - Oyster 800 (after images from [23])

Goal and scope of the two LCA studies

The goal of this study is to identify the environmental impacts of Oyster 1 and Oyster 800 over their lifetimes across three general categories: resource use, human health and ecological consequences. The analysis is carried out using Life Cycle Assessment methodology as defined by ISO 14040 and 14044 [24, 25]. The full cradle-to-grave life cycles of the devices are considered, separated into four stages: materials & manufacture (M&M), assembly & installation (A&I), maintenance (Maint.), decommissioning & disposal (D&D). The cut-off method was used for allocating recycling credit, such that only the reduced impacts of using recycled materials in the M&M stage were included, and any recycling at the end-of-life was considered only as avoided waste [26].

The case study for this analysis was for installation of one Oyster device at the European Marine Energy Centre (EMEC) wave test site in Stromness, Orkney. It is assumed that all materials are sourced from the global market, and components are manufactured in Europe. Where possible, installation data is based on real practices, as the Oyster 1 was installed at EMEC in 2008, and the Oyster 800 in June 2012.

The functional unit was chosen as 1 kWh, with all impacts reported per unit of energy output based on the total expected energy output of the Oyster WECs during their lifetimes. The 15-year lifetime output of Oyster 1 is expected to be 22.8 GWh at a capacity factor of 55% [7]. With a 20-year lifetime but the same capacity factor, the lifetime output of the Oyster 800 is estimated to be 77.1 GWh. While this capacity factor is higher than generally expected for wave energy technology, where values of 30% are more commonly stated [27], the unusual design of the power take-off system for the Oyster, incorporating an onshore hydro-electric plant and flywheel, has allowed the rated power of the generator to be optimised such that the capacity factor is higher [28]. Initial simulations and measurements at the EMEC test site found the capacity factor of the Oyster 1 to be over 60% [28]. In contrast the Pelamis WEC has a capacity factor at the same site of 45% [8, 29], while offshore wind has a capacity factor of around 40% [17].

A leading LCA software tool (SimaPro 8) is used which includes several life cycle inventory (LCI) datasets with input data on raw materials, production, transportation, and waste processing. The main source of LCI data used in this study is ecoinvent v3.01, a leading European-focused dataset which defines materials and emissions for a wide range of processes and products. 20 different impact potentials are studied by using three impact assessment methods: EDIP2003 and Cumulative Energy Demand (CED).

Input data

The data and information gathered for Oyster 1 were based upon the information available in Walker and Howell [7], which provided limited mass and materials data for the main components of the device. Additional data was sourced from publications by Aquamarine Power and their research partners [12, 13, 20, 21, 28, 30-32], and information from contractors involved in the project [33-37]. Although several component manufacturers were identified, there were some which were not known, so appropriate assumptions were made. One example of this was for the induction generator where materials data was sourced from an environmental product declaration published by ABB [38] and the manufacturing location was taken to be Helsinki, Finland, as this is the site of an ABB factory manufacturing such generators (ABB, personal communication, 3rd July 2015). As ABB was an investor in Aquamarine Power, this is considered a realistic assumption [39]. Where specific component information could not be identified, assumptions on materials and manufacturing processes were made based on information provided by some UK-based manufacturers (Heptron, personal communication, 10th July 2015; Gilbert Gilkes & Gordon Ltd., personal communication, 6th July 2015).

Most of the data for the Oyster 800 was sourced from the Environmental Statement and Decommissioning Document [12, 13], with additional details assumed to be the same as the Oyster 1. Details of the sources of data on components used in this analysis is provided in the Supplementary Material.

Materials & Manufacture

The key components of the two Oyster devices are illustrated in Figure 1, Figure 2 and Table 2.

Component			Oyster 1	Oyster 800	Function
Main	Device	Flap	✓	✓	Rotates forwards and backwards due to the wave motion.
		Seabed frame	✓	✗	A horizontal frame that stands on the seabed.
		Connector	✓	✗	Joins the main frame to the flap.
		Base frame	✗	✓	Supports for the flap and houses electrical components such as the control box [9];
		Rams (x2)	✓	✗	Converts the rotational motion of the flap into hydraulic energy.
		Hydraulic modules (x4)	✗	✓	

Auxiliary		Pipe spool assembly	✗	✓	This stainless steel component connects the directionally drilled pipelines to the converter
		Rock anchors (x2)	✗	✓	These facilitate installation and decommissioning.
		Can buoys (x4)	✗	✓	Installed for mooring and safety purposes.
		Sacrificial anodes	✗	✓	Protects against corrosion.
		Latching system	✗	✓	Secures the flap into the maintenance position.
	Pipeline	Pipeline	✓	✓	Contains the fresh water that moves the Pelton turbine on shore via hydraulic energy; 720 m for Oyster 1, 2x600 m (high-pressure and low-pressure) for Oyster 800.
		Concrete mattresses	✓	✓	Installed on the seabed to protect pipelines (3 of Oyster 1, 20 for Oyster 800).
	Onshore	Shipping containers (x2)	✓	✓	These house the electrical and mechanical equipment necessary for power generation.
		Support frame and bearings	✓	✓	These support the mechanical equipment in the containers.
		Induction generator	✓	✓	Installed capacity is 315 kW for the Oyster 1 and 800 kW for the Oyster 800.
		Pelton turbine	✓	✓	Converts hydraulic energy into mechanical energy.
		Flywheel	✓	✓	Provides smoothing of power generation.
	Subsea Infrastructure	Subsea infrastructure	✓	✗	Includes a pile connector frame forming the foundation for the seabed frame, four piles, and the pipeline system.

		Piles (x2)	✕	✓	The Oyster 800 has 2 piles and a different foundation system.

Table 2 - Description of components in Oyster 1 and Oyster 800

The materials used in each component are detailed in the Supplementary Material and summarised in Table 3. Although some mild steel is used, in order to calculate the results conservatively it was assumed that marine-grade or stainless steel will be used when information was unavailable, in line with the assumptions made by Walker and Howell [7]. As the ecoinvent database does not contain data on marine-grade steel, this has all been approximated as stainless steel. This assumption is tested in the sensitivity analysis.

Mass (t)	Oyster 1				Oyster 800			
	Device	Subsea infrastructure	Pipeline	Onshore equipment	Device	Subsea infrastructure	Pipeline	Onshore equipment
Stainless steel	16	164	85	3.6	742	190	20	3.6
Steel	100			7.5	2.0			11
Cement					500			
Concrete		67	45			180	72	
Glass-reinforced plastic					20		5.0	
Gravel					6.0			
Aluminium alloy anode					10			
Aluminium				3.2×10^{-3}				8.0×10^{-3}
Iron	0.40			1.0				2.5
ABS plastic					2.0			
Rubber					2.0			

Copper				0.40				1.0
Plywood				0.17				0.17
Brass	0.20							
TOTAL	116	231	130	13	1284	370	97	18

Table 3 - Materials breakdown for Oyster 1 and Oyster 800 [7, 12, 13, 20, 33, 34, 36-38, 40]. Further details are provided in the Supplementary Material.

Assembly & Installation

After the components are manufactured, they are transported to the assembly plant in Nigg (near Inverness), before the completed device is transported to the installation port at Stromness (Orkney). The installation of Oyster 1 took five months. Firstly, the pile connector frame was craned onto the seabed, piles drilled into the seabed and the piles grouted to complete the attachment to the frame [33]. The Oyster device was then towed to site and attached to the frame.

For Oyster 800, the first operation for the installation was the two foundation piles, which had been pre-installed by the time the WEC was brought onto the test site. The seabed was cleaned of seaweed and levelled with rocks to ensure the WEC could operate safely. After the latch system was installed, the main device was towed from the contractor's facility in Fife (north Edinburgh) to the test site [12].

The source locations for each component for Oyster 1 and Oyster 800 are given in Table 4, and further detailed in the Supplementary Material. All transportation to Stromness is a combination of land and sea travel. On land, it is assumed that the components are transported in lorries, which are selected from the ecoinvent dataset to be appropriate for the size and mass of each component. It was assumed that transportation at sea was by transoceanic ship, except for the final installation and the maintenance processes. Where specific manufacturers of components could not be identified, manufacturing distances were estimated based on the location of the highest concentration of manufacturers in the UK, which is Birmingham [41]. As can be seen in Table 4, this mostly includes components that are not specialised for the marine energy industry, such as flywheels and shipping containers, or components that are likely to be produced by existing manufacturing industries, such as concrete fabricators and steel mills. The effect of this assumption was tested by varying the distance travelled by these items by +/-10% and it was found to change the resulting environmental impacts by less than +/-0.1% for both Oyster devices (full results are provided in the Supplementary Material).

Component	Oyster 1		Oyster 800	
	Origin	Distance (km)	Origin	Distance (km)
Concrete mattresses			Birmingham	946
Flywheel	Birmingham	946	Birmingham	946
Hydraulic fluid	Stromness	0	Stromness	0
Induction generator	Helsinki	3252	Helsinki	3252
Oyster 1 main device	Nigg	254	n/a	n/a
Oyster 800 main device	n/a	n/a	Methil	398
Pelton wheel	Birmingham	946	Birmingham	946
Pile	n/a	n/a	Falmouth	1346
Pile grout	Copenhagen	1752	Copenhagen	1752
Pipeline	Birmingham	946	Birmingham	946

Shipping containers	Birmingham	946	Birmingham	946
Subsea infrastructure	Falmouth	1346	n/a	n/a
Support bearings	Katowice	3145	Katowice	3145
Support frame	Birmingham	946	Birmingham	946

Table 4 - Origin of components for Oyster 1 and Oyster 800

Installation, along with maintenance and decommissioning, was modelled according to the hours required for marine vessels to carry out a range of operations. Since no published information about vessel requirements and number of operation days for Oyster 1 was available these were derived from the information available for Oyster 800, along with the assumptions of Walker and Howell [7]. Data for the Oyster 800 was taken from the vessel requirement plans published by Aquamarine Power [12], adjusted to match published information about actual installation operations where they differed (Table 5). One example of this was the installation of the Oyster 800 piles, which took 34 operational days with a jack-up barge [34, 42]. The installation for the main device and its latches took at least 40 days, with the help of tugs, multi-cats and dive boats [34]. The onshore equipment was brought in with lorries and installed inside the shipping containers. The pipeline, after being assembled on the site, was directionally drilled from the shore towards the WEC [35]. The installation model does not take into account small components, such as bolts, or electrical connection equipment, but it does include vehicles, their resource consumption and pollutant emissions. The model also doesn’t include assembly procedures that took place onshore, as they are expected to be insignificant.

Stage	Timeframe	Tug	Jack-up	Multi-cat	Dive boat
Installation	Days on site	3	20 (34)	40	40
	Hours of operation per day	4	8	8	4
	Total hours per lifetime	12	160 (272)	320	160
Maintenance	Frequency of visits	-	-	Once every 5 years	3 (2) times per year
	Visits per lifetime	-	-	2 (3)	45 (40)
	Days on site per visit	-	-	20	20 (10)
	Hours of operation per day	-	-	8	4
	Total hours per lifetime	-	-	320 (480)	3600 (1600)
Decommissioning	Days on site	3	-	20	20
	Hours of operation per day	4	-	8	4
	Total hours per lifetime	12	-	160	80

Table 5 - Vessel Operation Information for Oyster 1 and Oyster 800. Where Oyster 800 differs this is represented in brackets.

Four types of vessels were used during the process: tugs, jack-ups, multi-cats and dive boats. Their total diesel consumption during the WEC's lifetime was calculated from hourly average fuel consumption data (Table 6) from sample commercial vessels and applied to each lifecycle phase.

Vessel	Hourly diesel consumption (in kg)
Dive boat [43]	30
Jack-up [44]	98
Multi-cat [45]	103
Tug [46]	488

Table 6 - Fuel consumption of marine vessels

Maintenance

The Oyster requires periodic maintenance visits in order to ensure it is working properly and repair any faults. For the Oyster 1 the frequency of visits is assumed to be three per year over its 15-year lifetime, as for the earlier study [7], while Oyster 800 is estimated to require two 10-day visits per year over a 20-year lifetime [12]. Each visit consists of four people travelling in two cars via a ferry from Edinburgh to the Orkney site. Offshore equipment will be inspected using a dive boat, as detailed in Table 5, and a detailed 5-yearly inspection will be carried out with multi-cats for possible repairs and component changes [12].

Decommissioning & Disposal

The decommissioning process is essentially the reverse of the installation process. The most notable difference is that large parts of the pile structures are not removed but left buried in the seabed [13]. 320 tonnes of material from the Oyster 1 and 1,325 tonnes from Oyster 800 is recovered and either landfilled or and recycled. It was assumed that the recovered material would travel to Aberdeen by ship, with 10% of the waste going to landfill and 90% recycled. The assumed recycling rate is typical for renewable generation technologies, as applied in previous studies by Vestas, Douglas et al. and Nicholson et al. [16, 47-49]. As the chosen recycling allocation method is the cut-off method, no credit is given for recycling at the end-of-life except in the avoided impacts of landfill.

Results

Life cycle impact assessment

The LCIA results are summarised in Table 7. The Oyster 800 performs better than its predecessor in all impact categories. This is a promising finding for the Oyster technology; however, it is important to note that Oyster 800 still has a considerable impact on the environment due to its material, fuel and infrastructure needs. Increased lifetime and higher energy production are the main reasons for the reduction in impacts.

Impact category	Unit	Oyster 1	Oyster 800	Difference
Global warming (GW)	g CO_2 eq/kWh	79	57	-28%
Ozone depletion (OD)	µg CFC-11 eq/kWh	3.2	2.5	-22%
Ozone formation - Vegetation (OFV)	m^2.ppm.h/kWh	0.58	0.39	-33%
Ozone formation - Human (OFH)	$x10^{-6}$ person.ppm.h/kWh	41	28	-33%
Acidification (A)	c m^2/kWh	76	55	-27%
Terrestrial eutrophication (TE)	c m^2/kWh	61	44	-28%
Aquatic eutrophication - N (AEN)	mg N/kWh	28	20	-28%
Aquatic eutrophication - P (AEP)	mg P/kWh	26	16	-38%
Human toxicity - air (HTA)	person/kWh	5642	2864	-49%
Human toxicity - water (HTW)	m^3/kWh	6.5	3.1	-52%
Human toxicity - soil (HTS)	$x10^{-3}$ m^3/kWh	64	34	-47%
Ecotoxicity water - chronic (EWC)	m^3/kWh	295	161	-45%
Ecotoxicity water - acute (EWA)	m^3/kWh	40	21	-47%
Ecotoxicity soil - chronic (ESC)	$x10^{-3}$ m^3/kWh	297	259	-13%
Hazardous Waste (HW)	mg/kWh	2.1	1.2	-44%
Slags/ashes (SA)	mg/kWh	403	295	-27%
Bulk waste (BW)	g/kWh	76	55	-27%

Radioactive waste (RW)	mg/kWh	2.7	2.0	-27%
Resources (R)	g/kWh	49	31	-36%
Energy (CED)	kJ/kWh	891	634	-29%

Table 7 - LCIA results for both Oyster devices, and the difference between them

Figure 3 shows the contribution of each life cycle stage to the environmental impacts. Due to the high material requirements of the Oyster WECs, it is not surprising that the M&M phase tends to have the largest impact. Furthermore, these are dominated by the impacts of steel. When the impacts are further broken down by component, the impacts of the offshore equipment dominate (see Supplementary Material). For the Oyster 1 these are fairly evenly divided between the device, subsea infrastructure and pipeline, while for the Oyster 800 the main device is responsible for around 60% of the total environmental impacts.

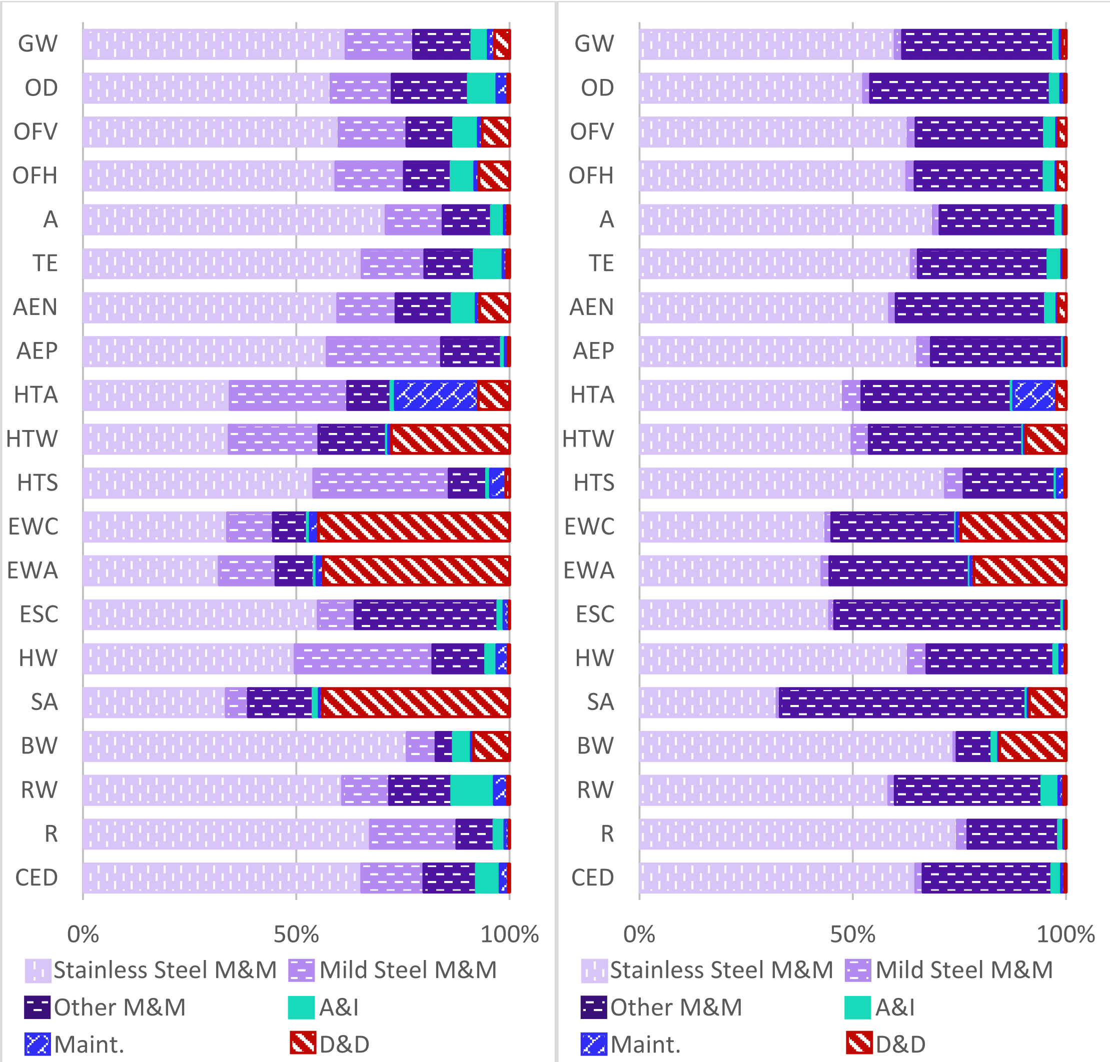

Figure 3 - Contribution of life cycle stages to impacts: (left) Oyster 1 and (right) Oyster 800. The abbreviations are described in Table 7. Materials & manufacturing impacts are divided to show the relative impacts of steel and other materials.

The global warming potential of Oyster 1 is found to be 79 g CO_2eq/kWh, and the energy intensity 891 kJ/kWh. These are 215% and 278% higher than the values calculated by Walker and Howell [7] respectively; however, the global warming potential is only 23% higher than the value calculated by Uihlein for a wave surge converter [9]. The source of the large difference in results from [7] was examined in detail and is presented in full in the Supplementary Material. It is found to be mostly due to differences in system boundary: the analysis by Walker and Howell was mostly based on the mass of the ten most used materials by weight, with only limited data on fabrication and excluding some significant components, such as the seabed frame and piles. Furthermore, the only transportation data included in the earlier study was transportation of the main device from the Nigg fabrication yard and the containers from Blyth. When the study presented here was re-run including only those components and processes considered by Walker and Howell, the discrepancy in results was reduced to 47% and 79% for carbon and energy respectively. This remaining discrepancy is likely due to methodological differences in considering credits for end-of-life recycling (which is a matter of ongoing debate in the LCA community [50]), and errors introduced by the use of two different sources of raw inventory data - the Inventory of Carbon and Energy [51] or ecoinvent [52]. This study is, therefore, considered an improvement on the earlier work by Walker and Howell, as it employs updated LCA techniques, is based on recent inventory data, and has a more comprehensive coverage of the device life cycle, including all major components, manufacturing processes and transportation.

A detailed examination of the process flows found that the processes that have the highest impact on global warming are hard coal and pig iron production, which are used in power generation and steel production respectively. The latter is responsible for almost 80% of the total GW impacts of the Oyster 1, and over 60% for the Oyster 800, as illustrated in Figure 3. The significant emissions from the A&I and maintenance stages are mostly due to the combustion of fossil fuels for transportation.

All life stages of both Oyster WECs produce waste for landfill. The Oyster 800 has a larger proportional bulk waste impact at the decommissioning and disposal stage due to lower waste production during manufacturing and relatively larger impacts resulting from landfill of concrete.

The carbon payback period is calculated to be 31 and 30 months for Oyster 1 and Oyster 800, based on annual average carbon emissions of UK electricity, which was 462 CO_2 eq/kWh in 2015 [53]. Energy payback, which is the expected time for the device to generate enough energy to offset the cumulative energy demand of its lifecycle (here calculated as 891 and 634 kJ/kWh, respectively) is 45 and 42 months, respectively.

Sensitivity Analysis

The sensitivity of these results to three key areas of uncertainty were tested: quantitative input data (i.e. all foreground data collected by the authors including mass of materials, material processing and transport requirements and sea vessel usage), design life and capacity factor. Full results of this sensitivity analysis are provided in the electronic supplementary material. It can be seen in Figure 4 that the sensitivity of impacts is similar across all categories for Oyster 1, except for human toxicity (air). Figure 5 shows the sensitivity response of two key impact categories for both Oyster models, and here it can be seen that the impacts for the Oyster 800 respond similarly to the Oyster 1, except that the HTA category is slightly more sensitive to changes in design life and slightly less sensitive to changes in input data than for the earlier model.

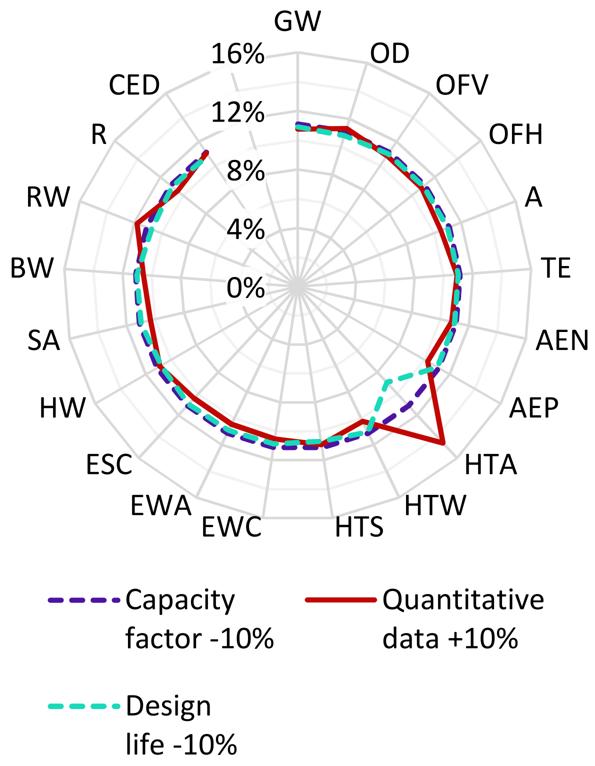

Figure 4 - Sensitivity of all impact categories to ±10% changes in capacity factor, quantitative input data and design life for Oyster 1.

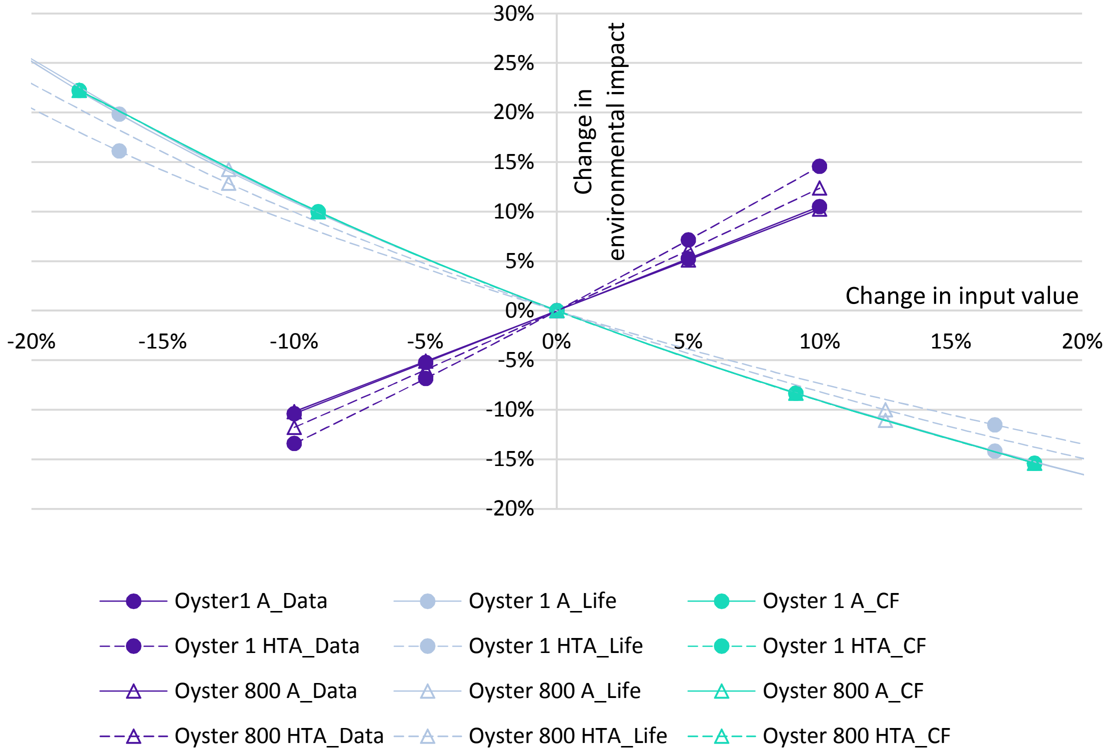

Figure 5 - Sensitivity of acidification (A) and human toxicity - air (HTA) impacts to changes in quantitative input data (Data), design life (Life) and capacity factor (CF). Note that all results for capacity factor are coincident.

Comparative analysis

It is useful to compare the results from this analysis against others. In an LCA the results for most impact categories can only be compared with those of other studies that employ the same impact assessment (IA) method, as the underlying characterisation factors and output units will vary across methods; for example, the EDIP2003 method expresses acidification impacts in square-metres representing “the area of ecosystem within the full deposition area which is brought to exceed the critical load of acidification as a consequence of the emission”

[54], while another leading IA method (ReCiPe2008) expresses the same impact in kilograms of sulphur dioxide equivalent, which is “therefore area independent” [55]. ([56] includes a detailed description and comparison of common IA methods.) The results of this study have, therefore, been compared with other types of power generation by using SimaPro to analyse detailed inventory data from the ecoinvent database with the EDIP2003 and Cumulative Energy Demand (CED) IA methods. The results are summarised in Figure 6. ~~Impacts for the Pelamis, which also employed these IA methods, have also been included for comparison.~~ It can be seen that both Oyster devices perform better than coal in most impact categories, and better than gas in 55-65% of the categories considered; however the Oyster is generally found to have higher impacts than other forms of low-carbon generation across most categories.

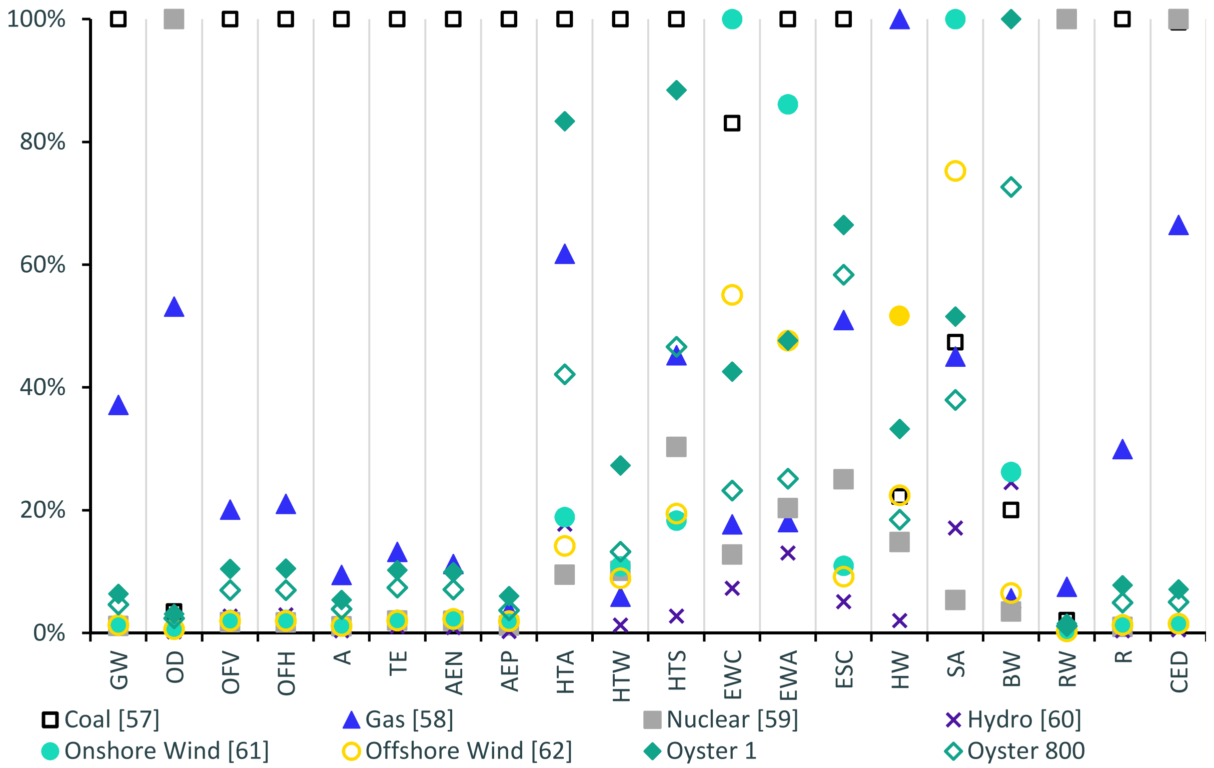

Figure 6 - Comparison of impacts of Oyster 1 and 800 with other types of generation [57-62]. Impacts are shown relative to the generation with the highest impact in each category.

Abbreviations: GW, Global warming; OD, Ozone depletion; OFV, Ozone formation -

Vegetation; OHV, Ozone formation - Human; A, Acidification; TE, Terrestrial eutrophication; AEN, Aquatic eutrophication - N; AEP, Aquatic eutrophication - P; HTA, Human toxicity - air; HTW, Human toxicity - water; HTS, Human toxicity - soil; EWC, Ecotoxicity water - chronic; EWA, Ecotoxicity water - acute; ESC, Ecotoxicity soil - chronic; HW, Hazardous Waste; SA, Slags/ashes; BW, Bulk waste; RW, Radioactive waste; R Resources; CED, Energy.

Although an accurate comparison of results between LCAs for most impact categories requires them to follow the same impact assessment method, comparison of studies employing different methods can still provide useful information in some instances. It is common practice, for example, to compare the embodied carbon and energy of renewable technologies, irrespective of the calculation methodology; all standard IA methods employ characterisation factors for embodied carbon based on data published by the Intergovernmental Panel on Climate Change (IPCC), and therefore there is relatively little variation between methods (identified as +/- 0.7% for the Pelamis WEC), while the authors have only identified two standard methods (CED and EPD) for calculating embodied energy, which also produce similar results (+/-4% for the Pelamis WEC) [56].

Figure 7 shows estimates of embodied carbon and energy impacts of on- and offshore wind, tidal barrage, tidal range and several wave converter devices and concepts. Note that some of the estimates for carbon footprint of wind power show a range; these values represent the range of carbon footprints found by a comprehensive meta-analysis of published life cycle assessments of wind power generation [15]. While the comparison of these types of renewable energy systems is useful to understand the relative extent of the environmental impacts, it should be noted that wind power is a much more established technology than marine energy, and the prototype Oyster devices in particular. This figure should not be used to draw conclusions on the likely environmental impacts of these devices when they reach technological maturity.

Again, it can be seen that the two Oyster devices (the first two sets of impacts on the graph) generally have higher impacts than any other wave, tidal or wind technology; however, this study has shown that the Oyster 800 was an improvement on Oyster 1. This would suggest that there is potential to further reduce impacts as the technology is refined. The carbon footprint for the Oyster 800 also aligns well with that calculated by Uihlein for a similar type of oscillating wave-surge device [9]. This is higher than for the Pelamis and other attenuator-type devices, probably due to the greater requirement for materials per unit of energy. Furthermore, it should be noted that the environmental impacts of fossil-fuelled power generation remain much higher than for the Oyster; for example, median life cycle GWP is 477 and 1001 g CO_2eq/kWh for natural gas and coal generation respectively [63]. This demonstrates the potential to reduce carbon emissions from power generation.

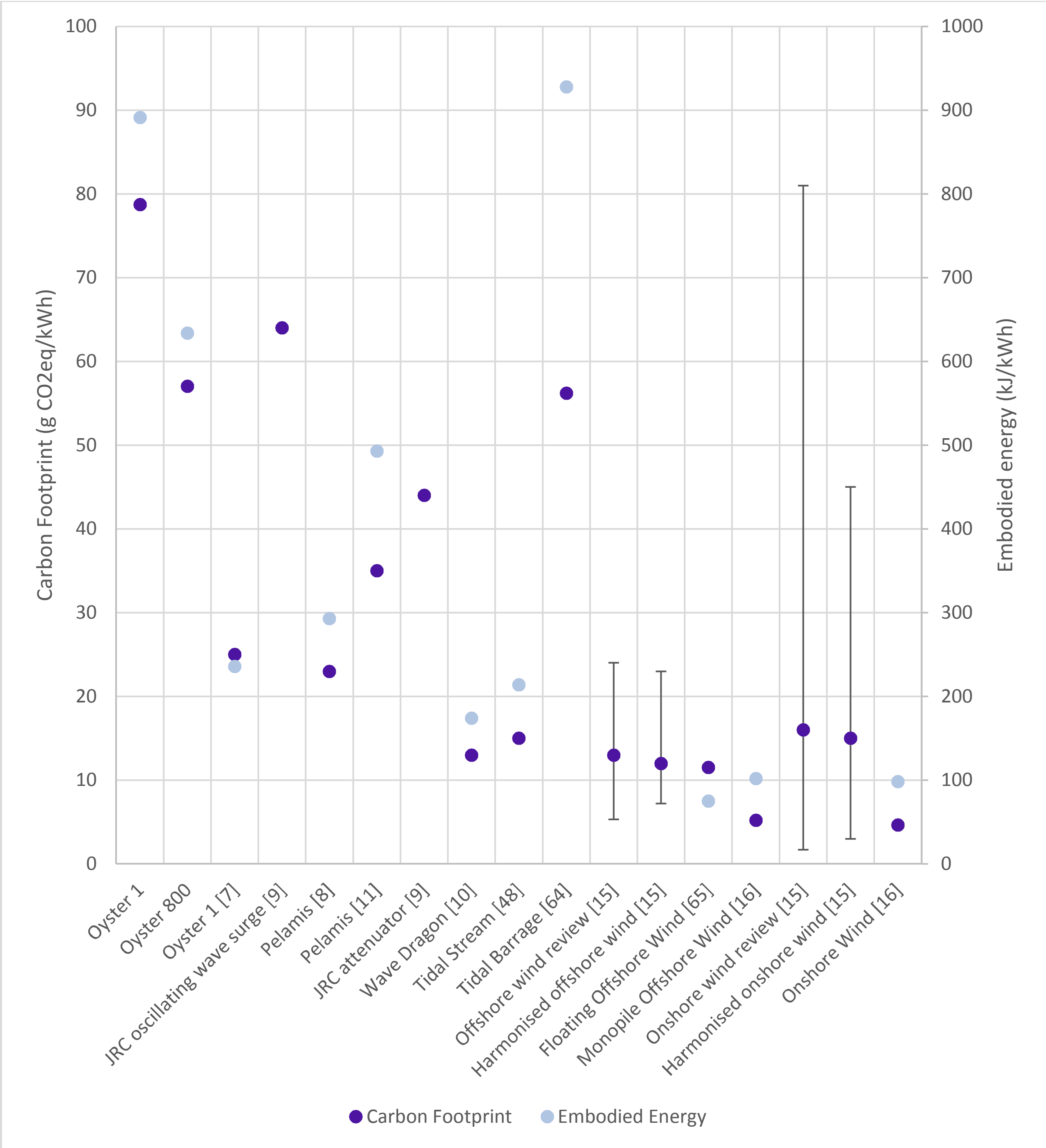

Figure 7 - Comparison of impacts from this study with other published studies [7-11, 15, 16, 48, 64, 65]

Limitations

This paper presents the environmental impacts for the Oyster 1 and Oyster 800 manufactured in the UK deployed at a single case study location - EMEC in Stromness, UK. Installing the device at a different location will affect the transport distances and the expected energy production. The sensitivity of the environmental impacts to transport distances are not explicitly presented in Figure 4 and Figure 5, so a further sensitivity test to isolate these was carried out, and the complete results are presented in the supplementary material. This test found that a change in onshore transport distances of +/-10% changed the environmental impacts of the Oyster 1 by an average of +/-0.6%, and the Oyster 800 by +/-0.2%. The impacts are even less sensitive to offshore transport distances, with a change of +/-10% only resulting in an average change of +/-0.03% and +/-0.02% for the Oyster 1 and Oyster 800 respectively. This demonstrates that small changes to transport distances are unlikely to significantly affect the findings of this analysis; however, installation at some distance from the manufacturing plant in the UK may require a further LCA to be carried out.

The sensitivity of the impacts to expected energy production was tested by varying the capacity factor (the ratio of expected energy production to maximum energy production) from 45% to 65%, and the results are illustrated in Figure 4 and Figure 5, and provided in detail in the Supplementary Material. It can be seen that the environmental impacts are highly sensitive to expected energy production; however, as this value is only used to present the results per kWh, it is straightforward to adjust the values for a different expected energy production due to a different wave profile at a different site. The results of this analysis can, therefore, be used to give a preliminary assessment of the likely environmental impacts of the Oyster devices at a range of locations.

One of the shortcomings of the study is the uncertainty surrounding the vessel requirements for A&I, maintenance and D&D stages, especially for Oyster 1. It is expected that emissions and energy consumption from these stages will be higher for the Oyster 800 due to its greater weight, but in the model used here this was not the case. Since no published information could be found, vessel requirements and number of operation days for Oyster 1 were derived from the information available for Oyster 800, along with the assumptions of Walker and Howell [7]. Furthermore, the sea vessel usage was approximated as operation of a barge on inland waterways, scaled for the appropriate fuel consumption and days of operation. Not only is this a significant approximation in itself, but it does not take into account the mass of components being transported, in contrast to all other analysis of freight transportation. Therefore, the actual impacts from A&I, maintenance and D&D stages might be higher. In order to test this, the input data for these sea vessels was changed by ±10% and it was observed that this changed the impacts by less than +/-0.05%, demonstrating that this assumption is unlikely to have a significant effect on the overall life cycle impacts of the Oyster WEC. (Full results of this analysis are given in the Supplementary Material.)

Paint, bolts, other electrical equipment, small mechanical components and onshore assembly data were not included in this analysis because it was assumed that their impacts would be relatively insignificant; this is in accordance with the guidance of ISO 14040 to avoid unnecessary effort calculating impacts for processes that will not significantly change the overall conclusions [24]. This reflects findings from other related work [7, 11, 16].

A breakdown of the results for steel by material type (Figure 3 and the Supplementary Material) shows that the impacts from stainless steel are very noticeable. Many of the Oyster components were modelled as stainless steel, as this was taken to be the closest approximation to marine-grade steel available in the LCI databases, but stainless steel has significant environmental impacts. In order to test this, the analysis was re-run with all stainless steel replaced with mild steel. This reduced the environmental impacts by an average of 26% for Oyster 1, but increased them by an average of 7% for Oyster 800 (the complete results are provided in the Supplementary Material). This difference is due to there being significant impacts from the cement used in the latching system for the Oyster 800 that are not reduced by a change of steel type. Furthermore, the global market mix of mild steel contains a significant proportion of primary material that has significant environmental impacts; however, switching to mild steel resulted in a reduction in both embodied carbon and energy, with impacts falling to 51 g CO_2 eq/kWh and 527 kJ/kWh, and 54 g CO_2 eq/kWh and 551 kJ/kWh for the Oyster 1 and 800 respectively. There is significant scope for the environmental impacts of the Oyster WEC to be further reduced in future design developments by reducing the quantities of steel and cement used in the device.

Both models for Oyster 1 and Oyster 800 include the installation of one wave energy converter. If these devices work in the form of arrays, both the embodied energy and the carbon footprint values could be expected to drop because they can share some of the major components; such as pipelines and the generator. The project from which much of the data for this study was sourced examined three Oyster 800 converters with a total installed capacity of 2.4MW [12]. It included two drive trains each composed of two Pelton wheels, one flywheel and one induction generator. In this study, since only one Oyster 800 was assumed to be installed, only one of each component was included in the model. This assumption was tested by analysing the results for the Oyster 800 assuming that it only required a share of the drive trains, and this was found to reduce the environmental impacts by an average of 2% (full results are in the Supplementary Material). Therefore, array applications are potentially more sustainable, but further detail of array designs is required to quantify this.

Conclusions

This paper presents a full life cycle assessment (LCA) of two generations of the Oyster wave energy device to examine their impacts on the environment, resources and human health. The impacts of the Oyster technologies were assessed at every stage of its life cycle, from cradle-to-grave. Recycling credit allocation was carried out with the cut-off method.

It was found that the environmental impacts of the Oyster 1 and 800 were similar. The high mass of the structures was found to cause the greatest environmental damage across most impact categories due to the extensive use of steel (both mild and stainless) in the devices. The impact of marine-grade or stainless steel is challenging to abate by replacement with mild steel, as it has been selected for its corrosion-resistant properties. The greatest potential for reduction of the environmental impacts of the Oyster devices therefore lies in reducing the steel requirement (per unit of energy production) or in considering alternative materials such as concrete.

Although it is much larger and heavier than the Oyster 1, the Oyster 800 performed better than its predecessor across all categories due its intended higher power output and longer life span. This demonstrates that the design development from Oyster 1 to Oyster 800 had a positive effect on the environmental impacts of the technology.

Although this analysis found that the Oyster devices had higher carbon footprint and embodied energy than other renewable energy converters, they were still significantly lower than for fossil-fuelled generation, demonstrating that this technology has the potential to contribute to the decarbonisation of electricity.

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